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Title: Storage and Reprocessing of Spent Nuclear Fuel

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Storage and Reprocessing of Spent Nuclear Fuel

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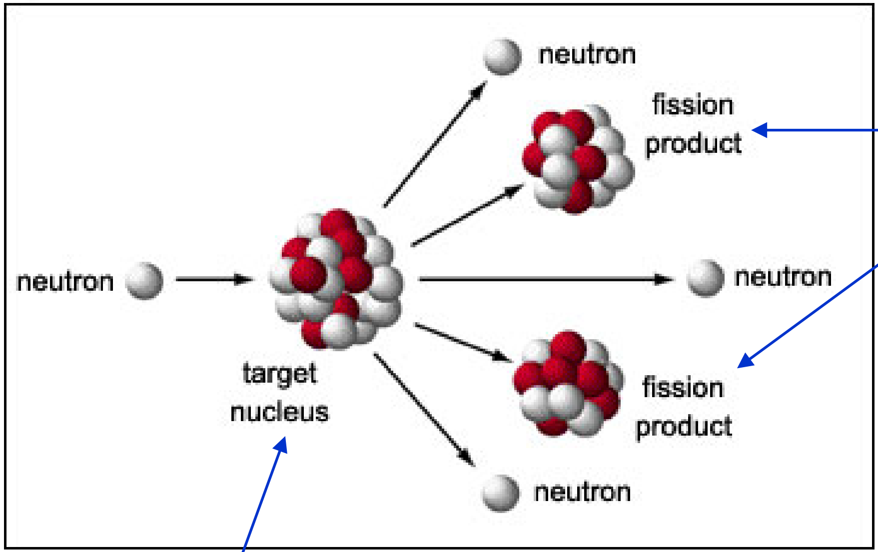
Introduction

- Following use in conventional nuclear reactors such as light-water PWRs and BWRs, the spent nuclear fuel has the following characteristics
  - ^{235}U enrichment down to ~ 1%
  - up to 1% Plutonium and
  - other actinides
  - Highly-radioactive fission products
- There are essentially two paths at this point
  - Long-term storage
  - Reprocessing

Fission Products

When fission occurs the parent nucleus splits into fission fragments and neutrons.



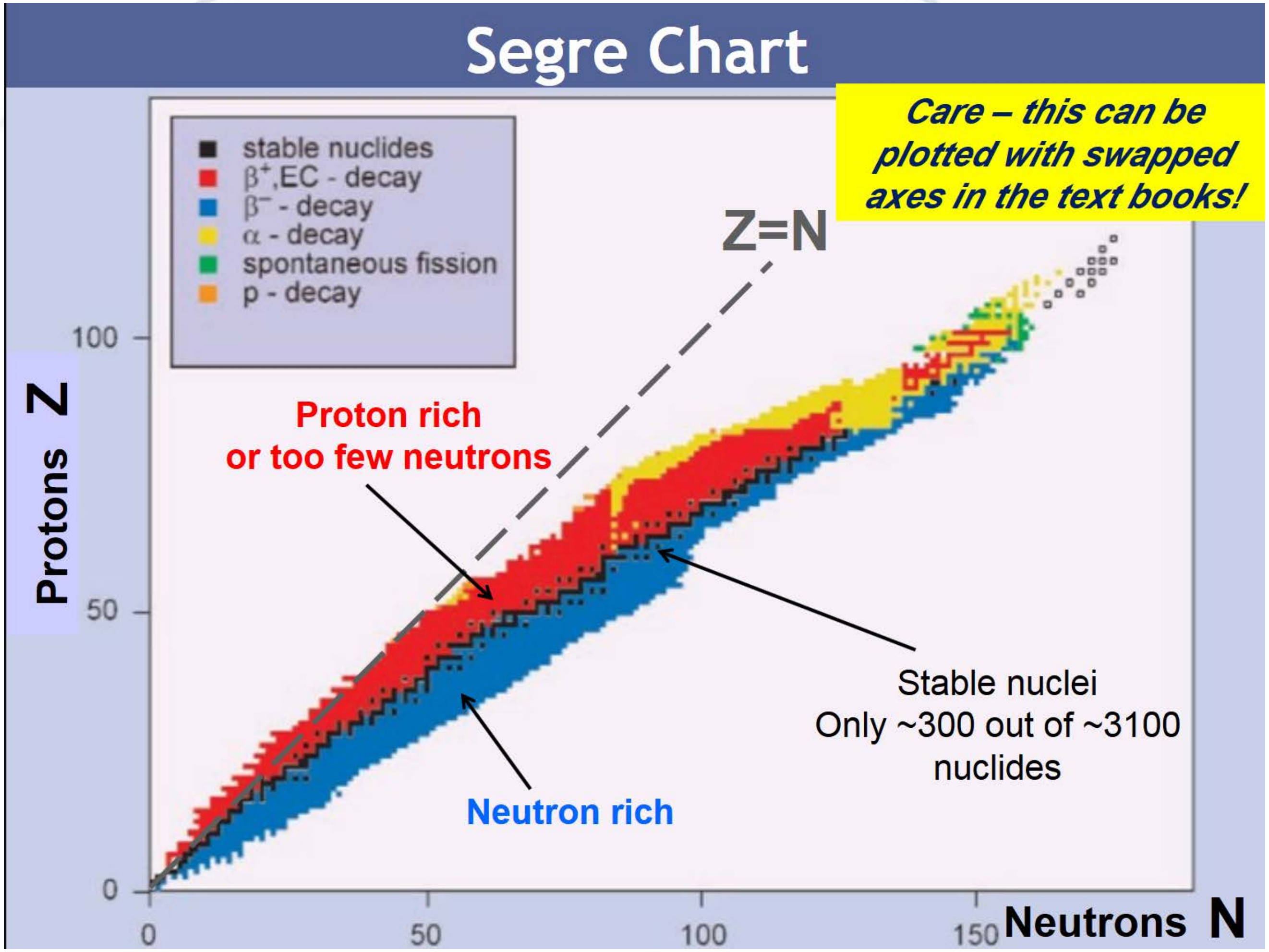
^{235}U (or ^{239}Pu etc.)

Fission products could be ^{141}Ba and ^{92}Kr for example but there is a range of possibilities.

^{137}Cs is one of the longer lived species ($T_{1/2}$ = 30 y) along with ^{90}Sr (28 y)

Gram for gram, fission fragments are far more radioactive than SNM

Stability & Proton : Neutron Ratio

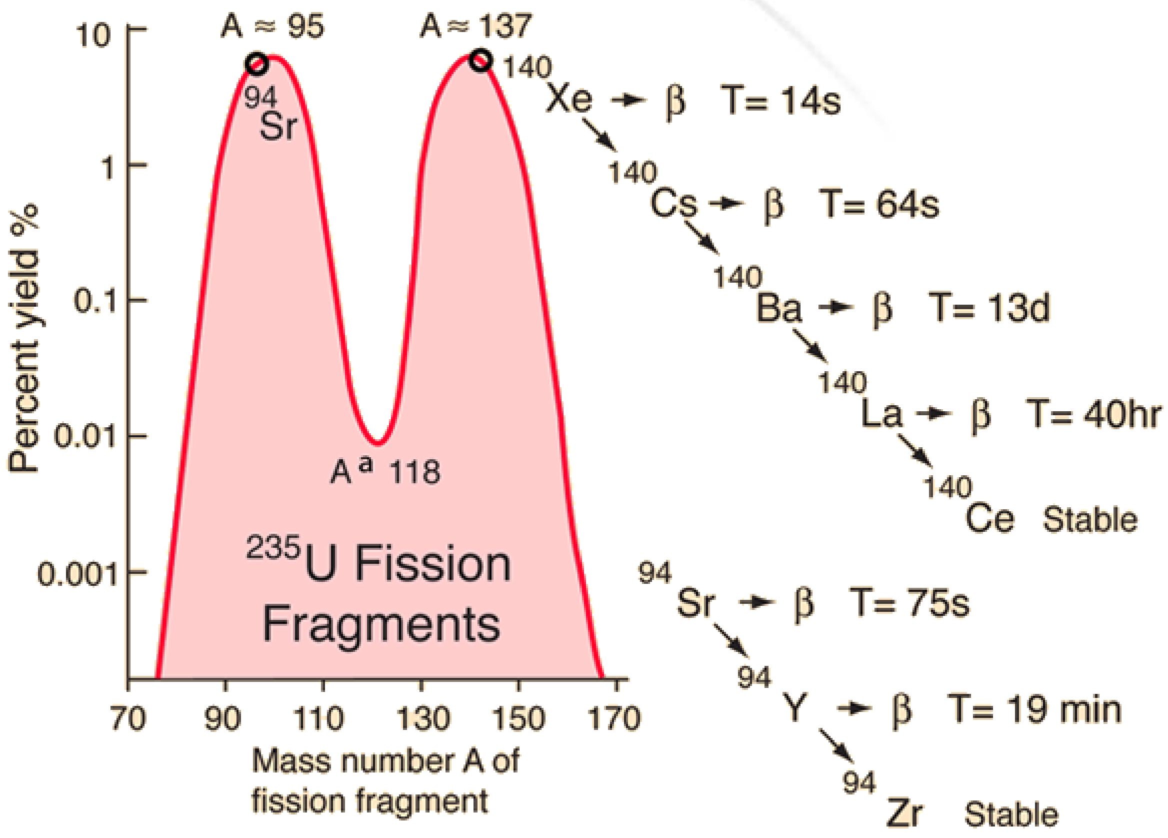


Fission Fragment Distribution

Fission products are typically unequal in mass and form a ‘bimodal’ distribution of mass vs. yield.

The reason for this is the larger neutron to proton ratio of the parent relative to the fragments.

Fission of heavy nuclei favors unequal mass fragments as they will be closer to the valley of stability.



Dose Rate from Spent Fuel

Recall: Lethal Acute Dose ~ 450 Rem

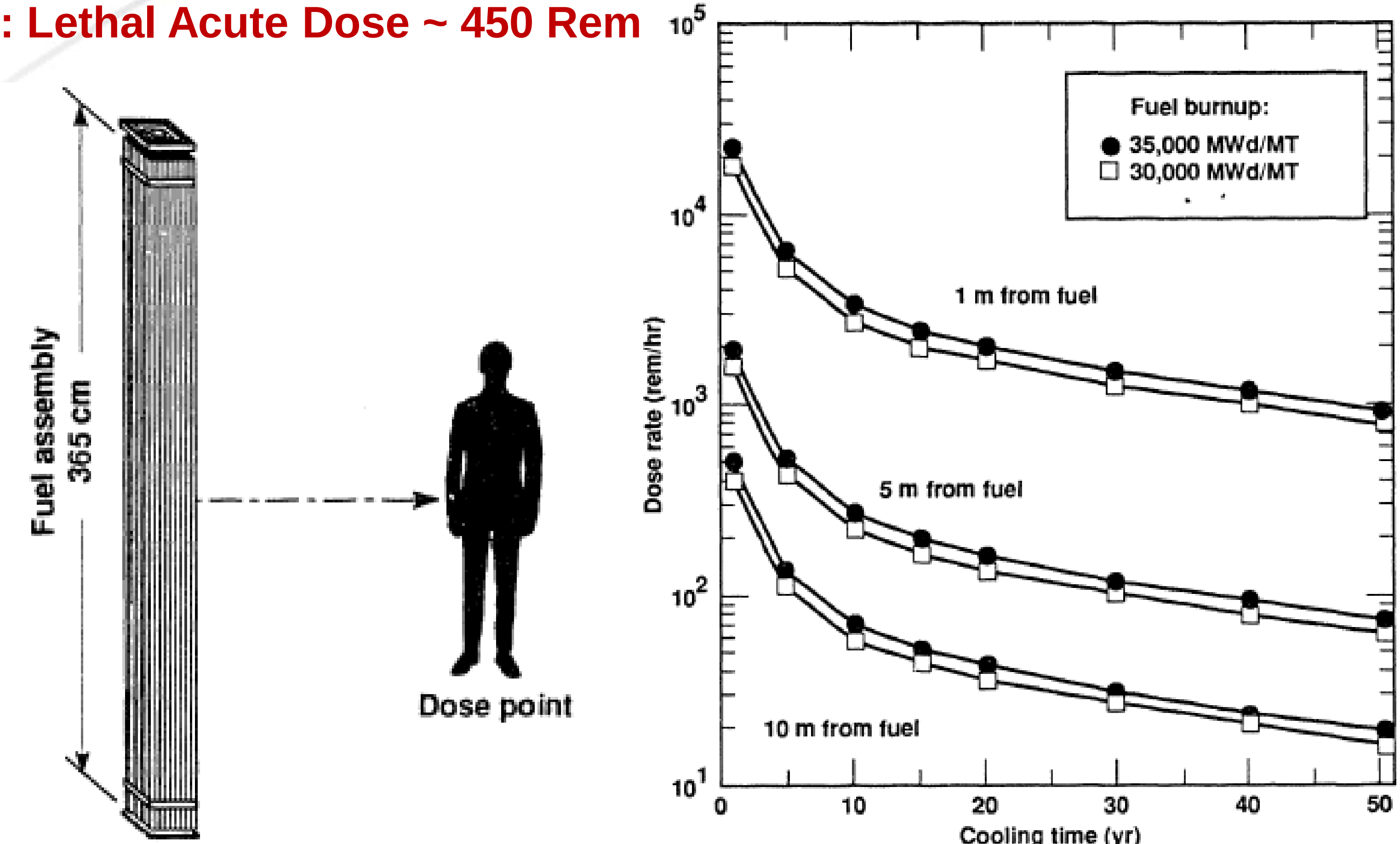


Figure 1. Dose rate from a PWR fuel assembly.

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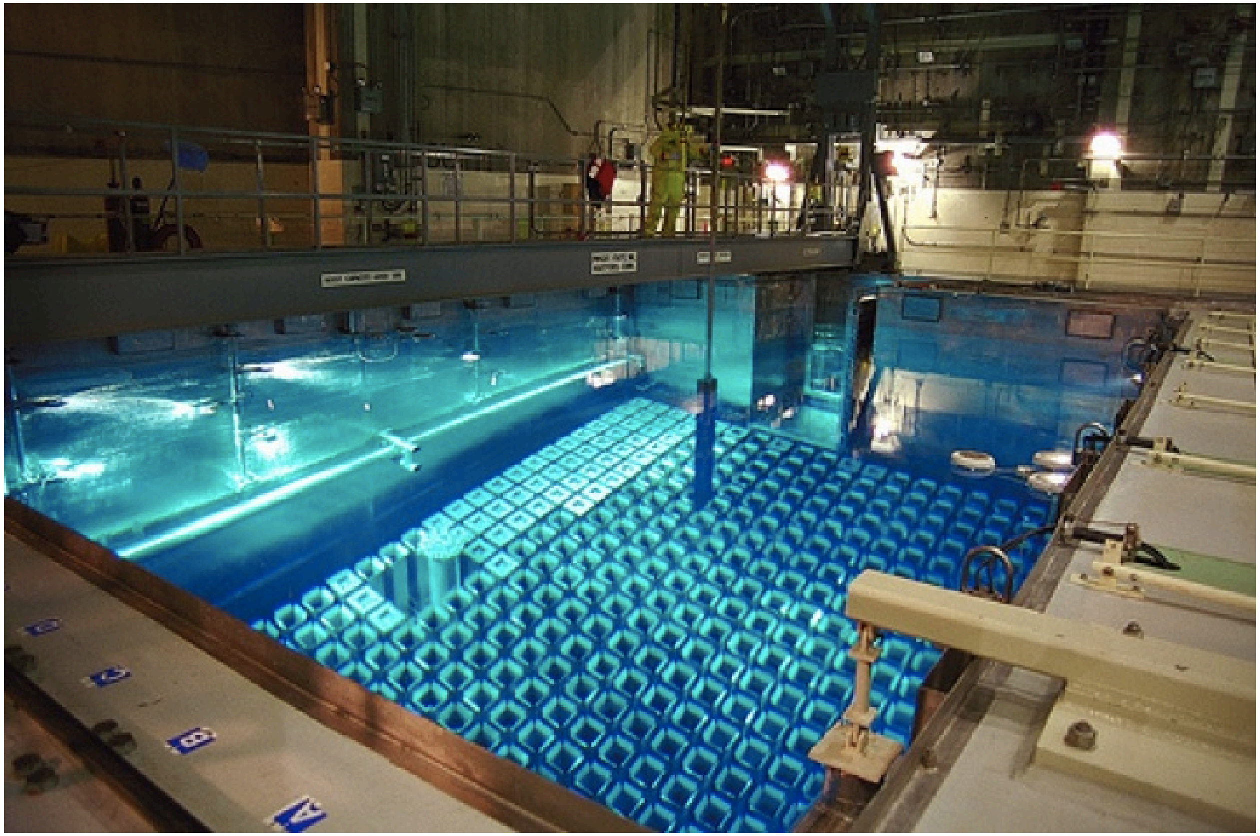
Spent Fuel Storage Options

- Spent nuclear fuel is stored in two main configurations
  - Spent-fuel pool
  - Dry cask storage
- No permanent underground storage facilities exist at this time although they have been proposed for decades

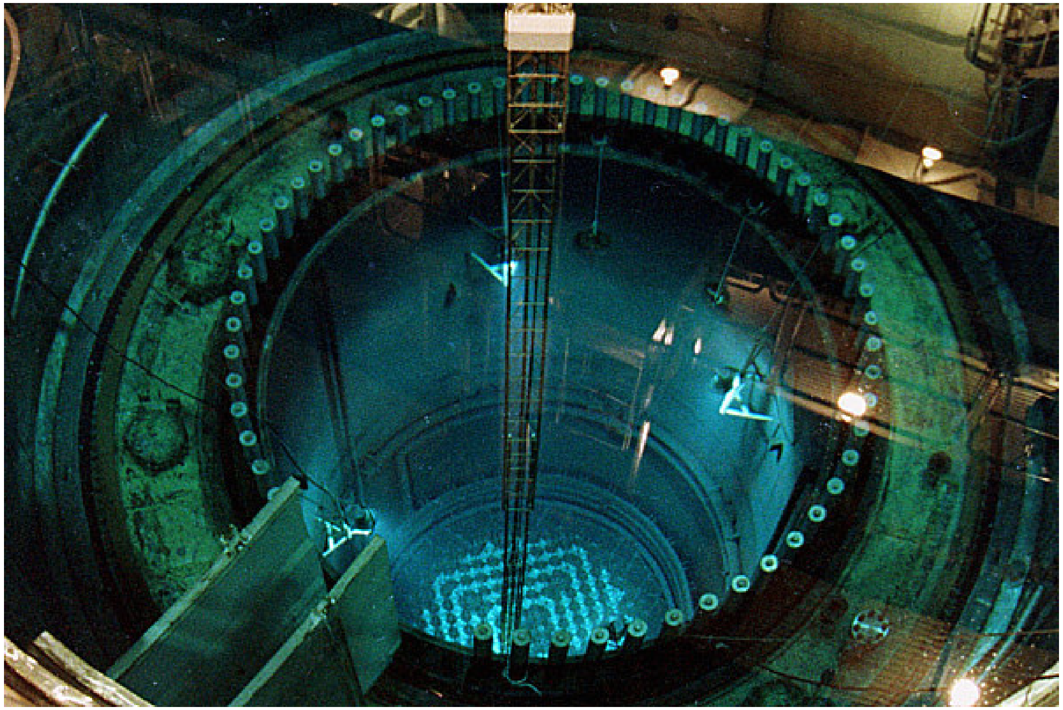
Spent Fuel Pool

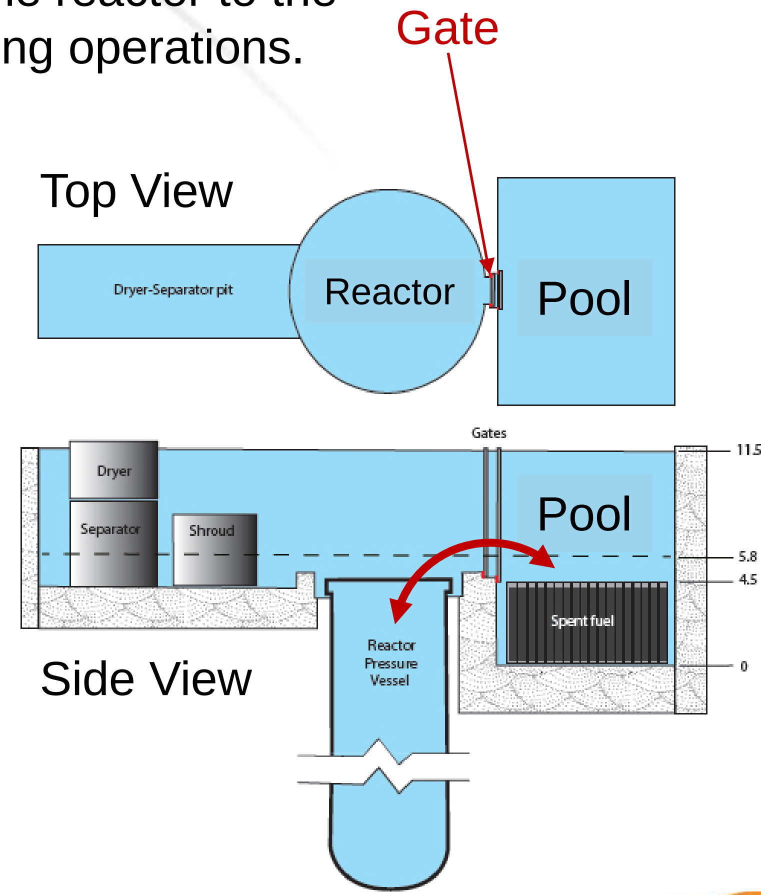
Most spent fuel at this time is stored in spent-fuel pools or ponds adjacent to the reactor. At least 20 feet of water is above the fuel and provides an adequate radiation shield and coolant.



Spent Fuel Pool Gate

Spent fuel is moved, entirely under water from the reactor to the pool through a gate that is opened during refueling operations.



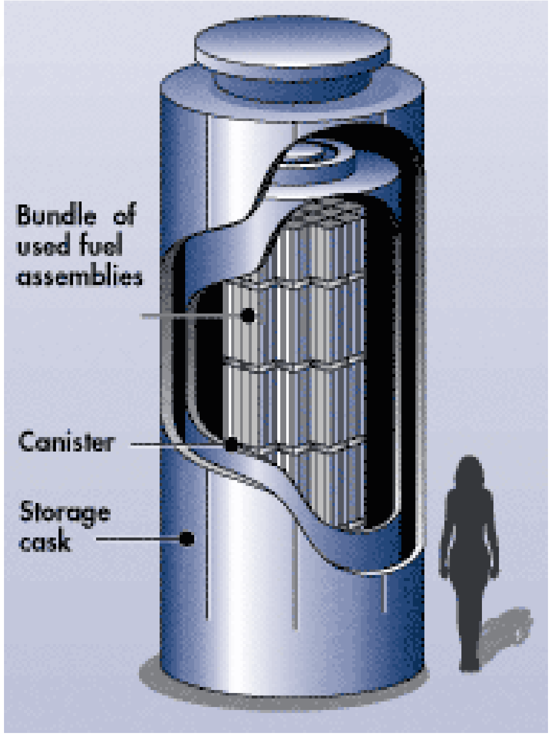


Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Dry Cask Storage

Dry cask storage allows spent fuel that has already been cooled in the spent fuel pool <u>for at least one year</u> to be surrounded by inert gas inside a container called a cask.

Designs and configurations vary but casks are typically substantial steel and concrete and purged with an inert gas.



https://www.nrc.gov/waste/spent-fuel-storage/dry-cask-storage.html

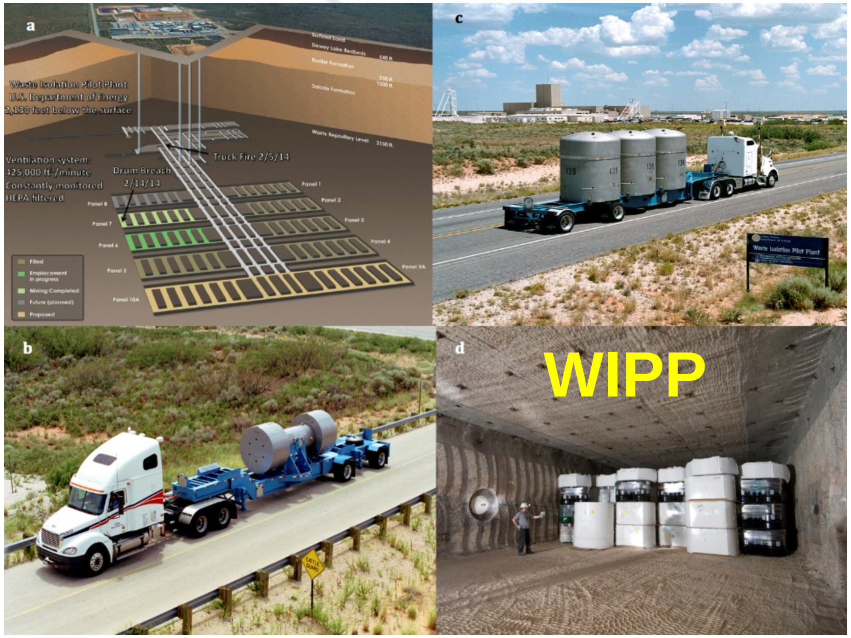
Dry Cask Configurations

A NRC *site-specific license* allows a specific cask design to be used at a specific location and offers the opportunity for a hearing before the NRC grants the license.

Horizontal Configuration

Vertical Configuration

Permanent Storage



1978: Initial DOE study began
2011: Federal Funding Ended

WIPP was originally designated for TRU waste from defense programs and has not yet be considered for spent nuclear fuel storage

NOTE: A repository is under construction as of 2016 in Onkalo, Finland as the world’s first spent fuel repository.

Reprocessing

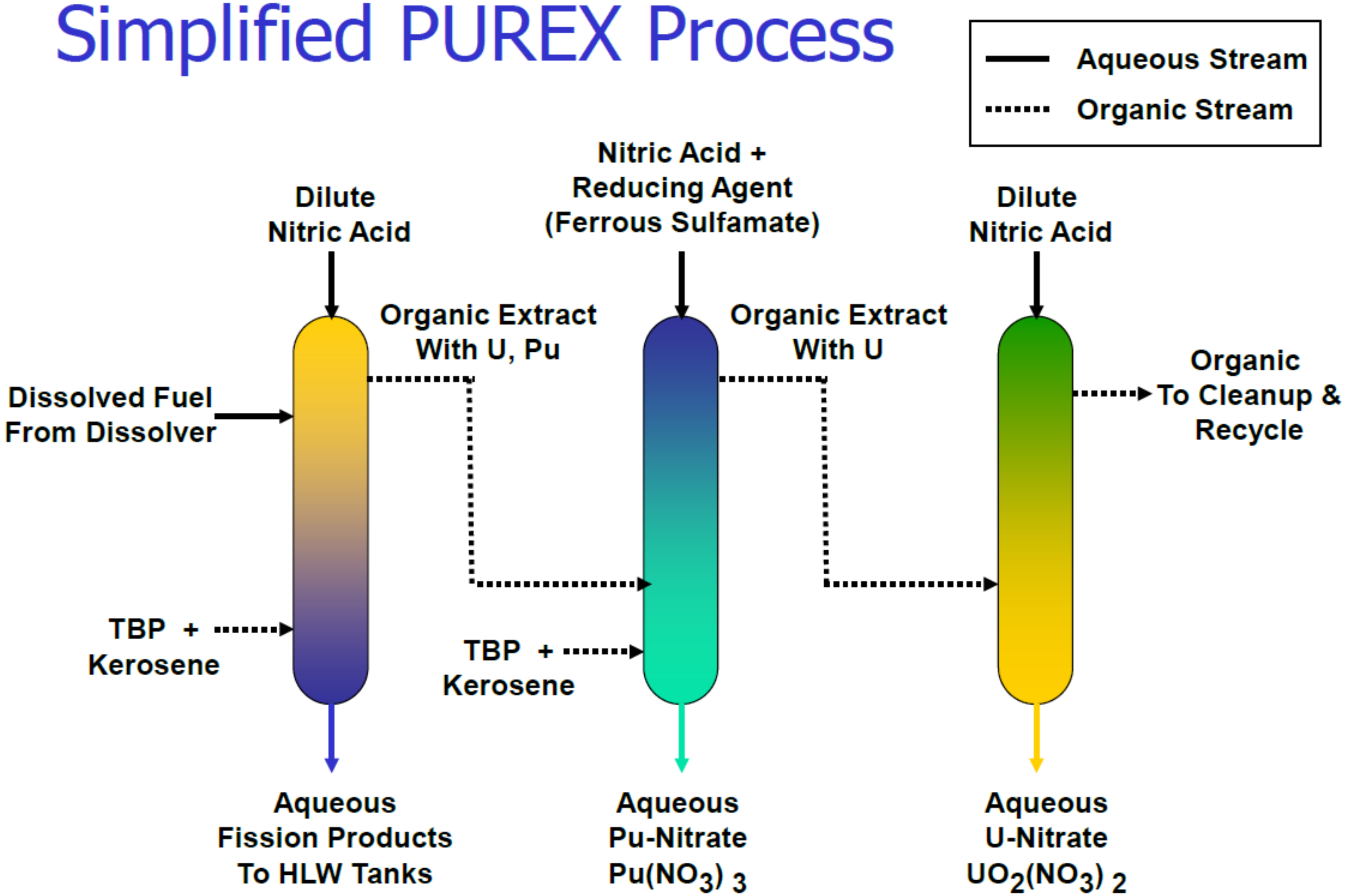
- In lieu of long-term storage, spent nuclear fuel can be reprocessed and fed back into the fuel cycle.
- Originally the goal of reprocessing was to recover fissile material such as ^{235}U and ^{239}Pu
- Newer reprocessing technologies will capitalize on fast neutron reactor technologies where a variety of long-lived actinides can be ‘burned’ without separation

PUREX

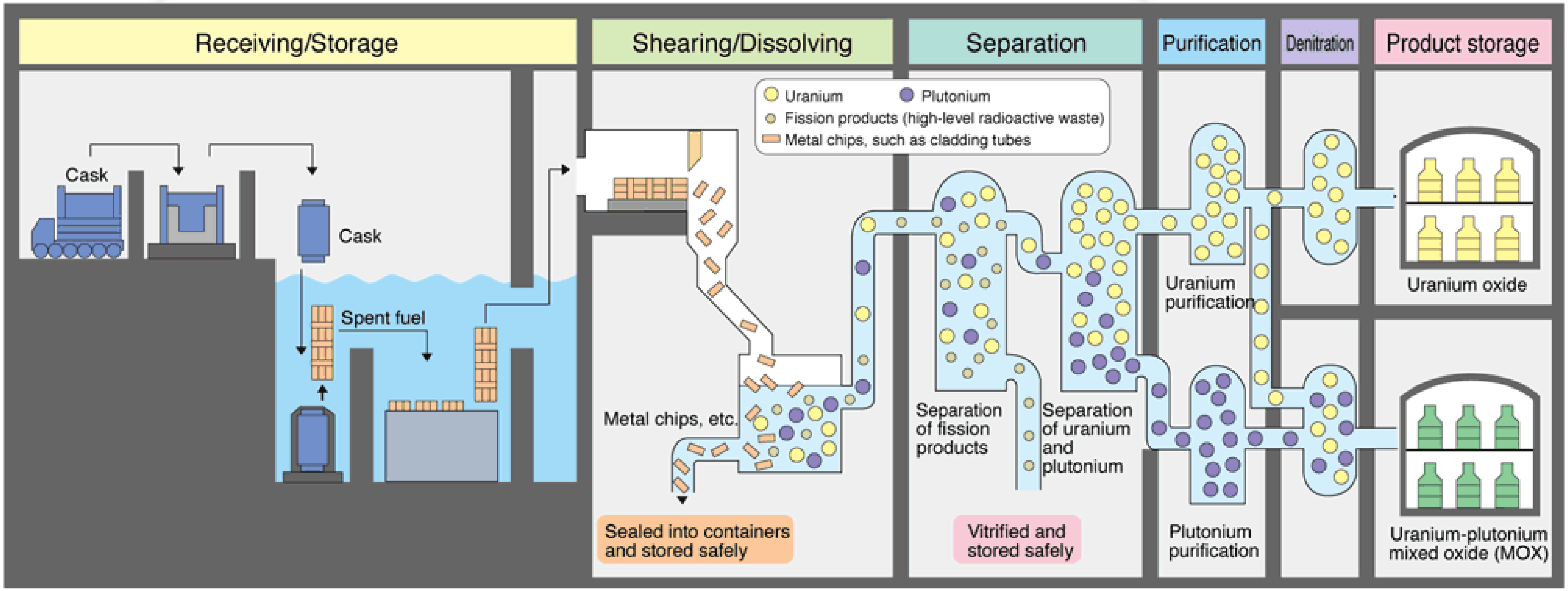
- The main historical process is called PUREX
  - Plutonium Uranium Redox Reaction
  - Invented at Univ. of Chicago during Manhattan Project
  - Used by all commercial reprocessing plants
  - Hydrometallurgical process
    - Aqueous solutions used to dissolve metal
- Basic concept
  - Fuel elements are chopped and dissolved in nitric acid
  - U & Pu are retrieved by solvent extraction
  - Remaining liquid is high-level waste and is calcined and incorporated into borosilicate glass

PUREX

Simplified PUREX Process



PUREX Flow and Practical Considerations



http://www.jnfl.co.jp/en/business/reprocessing/

Reprocessing in the USA

- Oak Ridge
  - Bismuth phosphate process 1943
  - Early solvent extraction work
- Savanah River and West Valley, NY operated until the 1970s
- 1976 President Gerald Ford suspends reprocessing and recycling of plutonium
- 1977 President Carter suspends reprocessing of spent nuclear fuel
- 1981 President Reagan lifts reprocessing ban but does not subsidize development

World Commercial Reprocessing

(tonnes per year)

LWR fuel	France, La Hague	1700
	UK, Sellafield (THORP)	600
	Russia, Ozersk (Mayak)	400
	Japan (Rokkasho)	800*
	Total LWR (approx)	3500
Other nuclear fuels	UK, Sellafield (Magnox)	1500
	India (PHWR, 4 plants)	330
	Japan, Tokai MOX	40
	Total other (approx)	1870
Total civil capacity		5370

** now expected to start operation in 2018*

Thermal Oxide Reprocessing Plant
Sellafield, UK

MOX

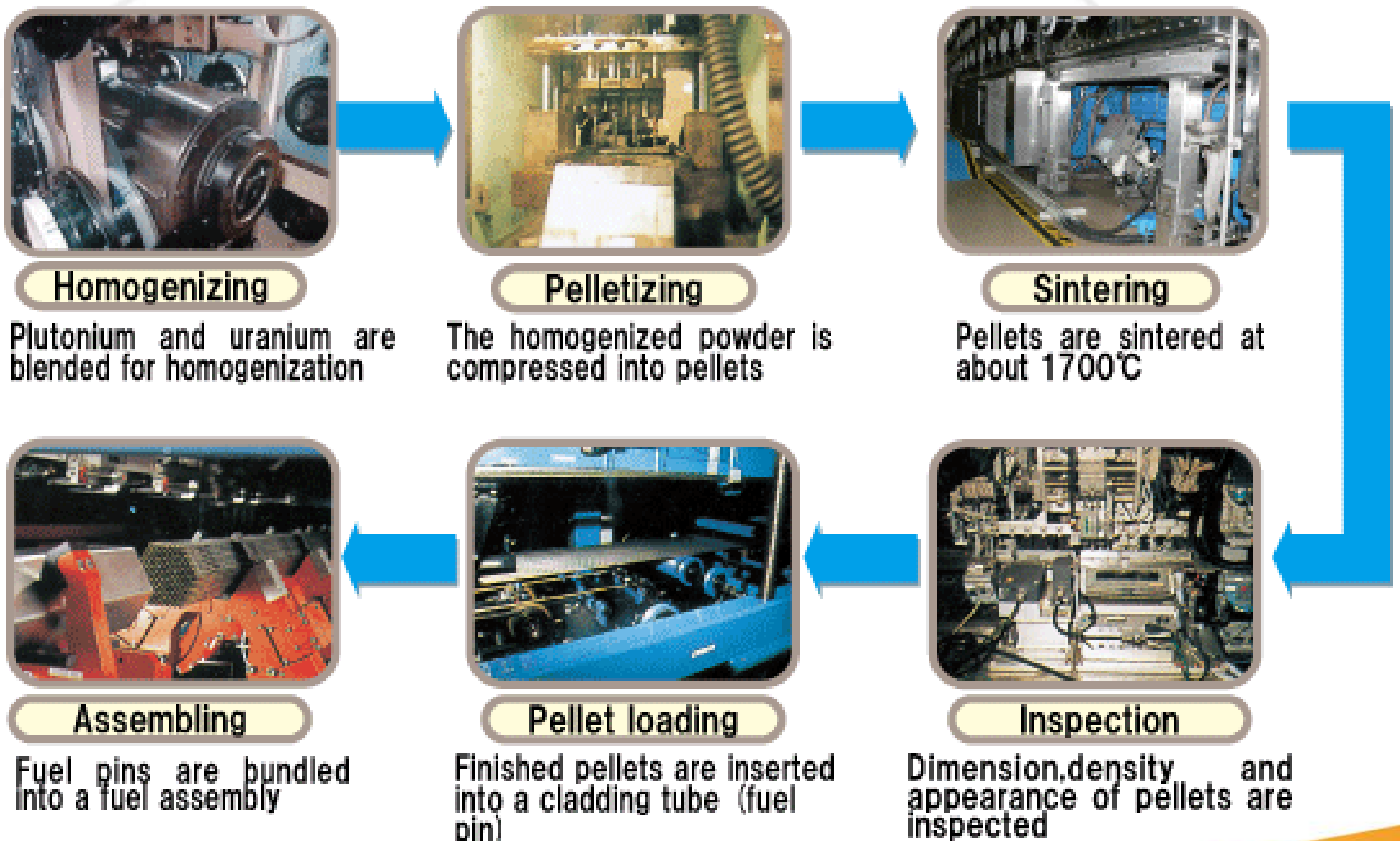
- Mixed-Oxide (MOX) fuel is composed of plutonium recovered from spent reactor fuel (or weapons) and depleted or natural uranium
- MOX is ~ 90-95% depleted or natural UO2 + ~5 – 10 % PuO2 depending on the grade of Pu
  - E.g. if WGPu then 5% Pu may be used in MOX
  - MOX will essentially behave like LEU in a reactor
- As of 2016, MOX provides ~5% of new nuclear fuel used today

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/mixed-oxide-fuel-mox.aspx

MOX Fuel Fabrication

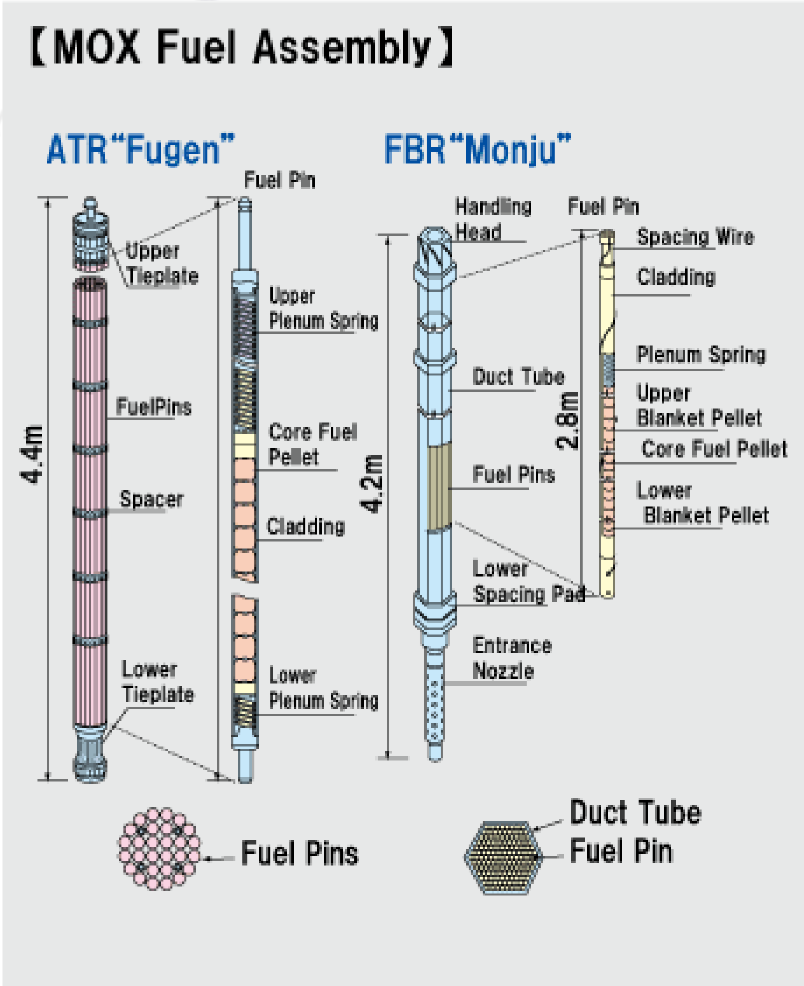
- The fabrication of MOX fuel is very similar to UO_2 fuel fabrication
  - The U and Pu oxides are separated in the reprocessing stage to produce UO_2 and PuO_2 powder
  - This powder is sintered and bonded into pellets
  - The pellets are then placed in fuel rods, and assemblies

MOX Fuel Fabrication

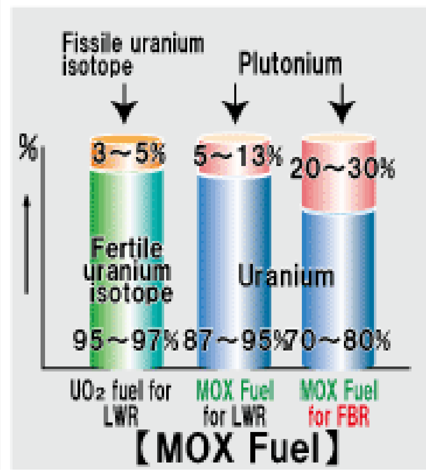


https://www.jaea.go.jp/english/04/tokai-cycle/03.htm

JAEA MOX Fuel Fabrication



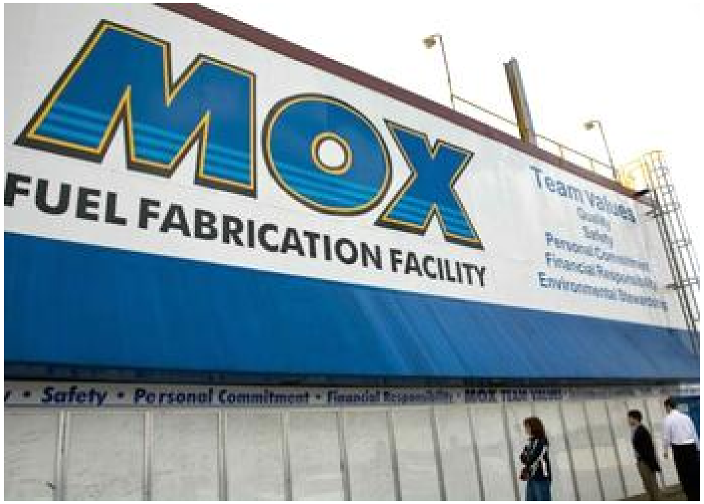
【Fuel pellets】
One fuel pellet for the FBR Monju is capable of generating approximately 1200KWh electricity, which is equivalent to the amount of electricity consumed in one household for a period of about four months. (Household power consumption:290 kWh/month)



https://www.jaea.go.jp/english/04/tokai-cycle/03.htm

MOX in the US

- Early work done in the 1960s and 70s
- CB&I AREVA, has been contracted by the NNSA to design, build, and operate a MOX Fuel Fab Facility at the Savannah River Site in Aiken, South Carolina.
- Intended to convert surplus WGPu into MOX fuel



MOX Fabrication Worldwide

World mixed oxide fuel fabrication capacities (t/yr)

	2009	2020
France, Melox	195	195
Japan, Tokai	10	10
Japan, Rokkasho	0	130
Russia, Mayak, Ozersk	5	5
Russia, Zheleznogorsk	0	60?
UK, Sellafield	40	0
Total for LWR	**250**	**400**

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/mixed-oxide-fuel-mox.aspx

Use of plutonium in MOX in the EU

	kg Pu from reprocessing	Tonnes natural U saved (est)	Thousand SWU saved (est)
2011	9,410	824	571
2012	10,334	897	622
2013	11,120	1047	740
2014	11,603	1156	825
2015	10,780	1050	742

Source: Euratom annual report 2015, annex 5.

MOX Reactors Worldwide

- ~40 reactors in Europe and 10 in Japan are licensed to use MOX fuel
- China and Russia will mainly focus on use of MOX in fast reactors
- If less than ~ 50% MOX is used in a ‘conventional’ reactor then only minor modifications need to be made
  - E.g. more control rods are needed

Storage of Reprocessing Waste

- High-level waste generated from production of MOX fuel must be stored for decades in casks on site until a permanent repository is built
  - Note: the owner of the material may be responsible for the waste even if they are not the reprocessing entity
    - E.g. Contracts between Japan, France, and UK to ship waste back to Japan (prior to Japan having native reprocessing capabilities)

Summary

- Addressing the problem of waste, especially high-level waste (HLW), is a requirement of the nuclear fuel cycle that cannot be ignored.
- The current options are:
  - of long-term but not permanent, storage in spent-fuel pools or dry-cask storage
  - Reprocessing / use in MOX fuel
  - No permanent HLW repository has yet been completed